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## **Controls on sediment production from an unpaved resource road in a Pacific maritime watershed**

van Meerveld, H J ; Baird, Elizabeth J ; Floyd, William C

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DOI: <https://doi.org/10.1002/2013WR014605>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-100768>

Journal Article

Published Version

Originally published at:

van Meerveld, H J; Baird, Elizabeth J; Floyd, William C (2014). Controls on sediment production from an unpaved resource road in a Pacific maritime watershed. *Water Resources Research*, 50(6):4803-4820.

DOI: <https://doi.org/10.1002/2013WR014605>



## Water Resources Research

### RESEARCH ARTICLE

10.1002/2013WR014605

#### Key Points:

- Rainfall simulation was used to study key controls on sediment generation from an unpaved road
- Rainfall intensity and number of loaded truck passages controlled sediment production
- Elevated concentrations persisted for 30 min or less following the passage of a loaded truck

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#### Citation:

van Meerveld, H. J., E. J. Baird, and W. C. Floyd (2014), Controls on sediment production from an unpaved resource road in a Pacific maritime watershed, *Water Resour. Res.*, 50, 4803–4820, doi:10.1002/2013WR014605.

Received 18 AUG 2013

Accepted 12 MAY 2014

Accepted article online 15 MAY 2014

Published online 12 JUN 2014

## Controls on sediment production from an unpaved resource road in a Pacific maritime watershed

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**Abstract** Unpaved resource roads have the potential to produce large amounts of sediment and can negatively impact water quality and aquatic ecology. In order to better understand the dominant controls on sediment generation from unpaved resource roads, we did 23 large-scale rainfall simulation experiments on a road section in the Honna Watershed, Haida Gwaii, British Columbia, Canada. The experiments were performed with different rainfall intensities (4–52 mm/h), with and without traffic. Precipitation intensity was the dominant control on the amount of sediment generated from the road surface; the total mass of sediment increased linearly with precipitation intensity. The number of passages of loaded logging trucks during an experiment was the second most dominant control on the total amount of sediment generated from the road surface. Elevated sediment concentrations in road surface runoff persisted for 30 min following the passage of loaded logging trucks during low intensity (<8 mm/h) rainfall events and for much shorter periods at higher rainfall intensities. The mass of sediment generated by the passage of a loaded truck increased with precipitation intensity. Passages of empty logging truck did not result in sediment pulses, except during very high rainfall intensities. Seven small-scale rainfall simulation experiments on other parts of the road, however, highlight the large spatial variability in sediment production from the road surface, suggesting additional experiments are required to better describe and predict sediment production from different road sections.

### 1. Introduction

Resource roads affect hydrological and geomorphologic processes by changing natural drainage patterns and altering the amount and distribution of overland flow [Jones *et al.*, 2000; Gucinski *et al.*, 2001; Wemple *et al.*, 2001; Ziegler *et al.*, 2001a; Croke *et al.*, 2005; Sidle and Ziegler, 2012; Buchanan *et al.*, 2013a]. Infiltration capacities of resource roads are generally much lower than those of the surrounding landscape [Spinelli and Marchi, 1996; Ziegler and Giambelluca, 1997] and have been estimated to be as low as 0.1–0.8 mm/h [Reid and Dunne, 1984]. These low infiltration capacities are critical to the functioning of the road, but cause infiltration excess overland flow, even for low intensity events [Ziegler and Giambelluca, 1997; Croke *et al.*, 2005]. Resource roads can also intercept subsurface flow and redirect it overland [Spinelli and Marchi, 1996; Wemple and Jones, 2003], resulting in enhanced flow rates, increased erosion [MacDonald *et al.*, 2001; Negishi *et al.*, 2008; Sidle and Ziegler, 2012; Buchanan *et al.*, 2013b] and increased hillslope-stream connectivity [Croke *et al.*, 2005; Buchanan *et al.*, 2013b; Latocha, 2013].

Unpaved resource roads have the potential to produce large amounts of sediment [Luce and Black, 1999, 2001; Reid and Dunne, 1984; Rijdsdijk, 2005] and can supply the majority of sediment to streams in some forested areas [Reid and Dunne, 1984], especially where mass failures are infrequent [Bilby *et al.*, 1989]. Sediment generated from resource roads impacts aquatic ecology and water quality in nearby streams [Ramos-Scharrón and MacDonald, 2007]. Suspended sediment reduces the amount of light available for photosynthesis [Ramos-Scharrón and MacDonald, 2007], can irritate fish gills [Bilby, 1985], and lead to acute fish mortality [Swinkels *et al.*, 2014]. Increased sedimentation in small mountain streams may clog gravel used as fish spawning areas and reduce survival rates following spawning [Beschta, 1978]. Degradation of stream ecology and water quality due to sediment is one of the most studied effects of the building, use and maintenance of roads in forested areas.

The potential sediment sources in an unpaved resource road prism include the road surface, cut slopes, fill slopes, and/or ditches [Spinelli and Marchi, 1996; Fu *et al.*, 2010]. The amount of sediment available from the road surface is related to surface type (including surface material), surface dimensions, surface gradient, and traffic intensity [Akay *et al.*, 2008; Fu *et al.*, 2010]. The texture of the material on the road surface strongly affects sediment yields. Silt-sized particles are most easily dislodged and transported in suspension via overland flow. Larger particles are eroded at a lower rate as they are moved in traction and saltation, while very fine soils with high clay content are less erodible due to particle aggregation [Luce and Black, 1999]. Fine sediment on unpaved road surfaces is generally derived from the breakdown of surface material as vehicles pass and/or the upward forcing of fine-grained sediment from the road bed as traffic pushes the surface material into the bed [Reid and Dunne, 1984; Ziegler *et al.*, 2001b]. High-quality road aggregate can resist crushing by traffic, limiting the amount of sediment available for transport [Rodgers *et al.*, 2009; Foltz, 1996]. The importance of aggregate quality increases as traffic and rainfall increase [Foltz, 1996]. High-quality aggregate, however, is not always locally available and transport costs can make importing suitable aggregate uneconomic. Designing and building roads with highly permeable materials, shortened road length segments, and shallow slopes mitigates erosion and transport of sediment [Fransen *et al.*, 2001].

Precipitation intensity and amount should be a primary control on sediment production from unpaved resource roads and the transport capacity of road runoff [Bilby *et al.*, 1989; MacDonald *et al.*, 2001]. However, some studies have found either poor or nonsignificant relations between precipitation intensity (or proxies of precipitation intensity) and sediment concentrations [Reid and Dunne, 1984; Croke *et al.*, 2006]. Bilby *et al.* [1989] suggested that precipitation variables, including total precipitation amount, may not be significantly related to sediment concentrations due to the supply-limited nature of appropriate sized sediment and compacted road surfaces producing overland flow regardless of precipitation amount. In the absence of repeated disturbance, sediment concentrations are greatly reduced after the first few minutes of rainfall due to the limited supply of fine sediment and the development of a thin layer of flow and particle armor that protect the road surface against splash [Arnáez *et al.*, 2004; Ziegler *et al.*, 2001b].

Traffic (including logging trucks, dumps trucks, passenger vehicles, and motor cycles) is the primary cause of disturbance on unpaved resource roads, leading to the breakdown of armor layers and resupply of available sediment. Traffic can lead to increases in sediment yield during precipitation events that persist for tens of minutes following a passage [Luce and Black, 2001; Ziegler *et al.*, 2001b]. How this traffic-induced sediment pulse is affected by rainfall intensity is still unclear. Resupply of sediment can also occur during dry weather as a result of traffic or road maintenance. Traffic can also alter the physical properties of the road increasing both the erosive power and transport distances of suspended sediment. Cross-slope flattening, for example, directs water down the road surface as it travels to side ditches, increasing the distance required for water to flow off the road and increasing the transport capacity [Foltz, 1996]. Roads with high traffic intensity or whose surface is not well maintained may progress from cross-slope flattening to rut development. Overland flow concentrated in ruts will have a higher shear stress, increasing its ability to erode and carry sediment [Foltz, 1996]. Road maintenance to prevent rutting and pot hole development (e.g., grading) can increase the amount of sediment generated from forest roads, so it is generally recommended for this work to be done in dry weather. Several studies have shown that sediment yields decline significantly in the second and third year after grading or road building because of the decrease in the supply of readily available material due to armoring [Luce and Black, 2001; Megahan *et al.*, 1986; Ramos-Scharrón and MacDonald, 2005; Sugden and Woods, 2007].

The intensity and duration of road use can explain the spatial variability in resource road erosion and sediment concentrations. Reid and Dunne [1984] and Croke *et al.* [2005] showed that a large portion (68% and 95%, respectively) of the observed variation in sediment concentrations was accounted for by road use. MacDonald *et al.* [2001] showed that a heavily used road segment produced at least twice the amount of sediment than a similar road section without any truck traffic. Similarly, Bilby *et al.* [1989] found the total number of axles since the last storm, total axles during the storm, and time since ditch flow began were most strongly related to sediment concentrations in ditch flow. This relation, however, does not hold for extremely heavy traffic (>100 axles/d), which was explained by the accumulation of fine sediment buffering the road surface from further abrasion and sediment production. Contrary to these results, Ramos-Scharrón and MacDonald [2005] showed that traffic did not significantly affect sediment production rates.

These previous studies on sediment production from unpaved resource roads have shown that different processes control erosion and sediment transport from a road prism, with many processes acting simultaneously, but to different degrees. We are therefore not yet able to reliably predict the dominant controls and physical processes affecting the amount of sediment generated from unstudied resource roads [Luce, 2002]. This limits our ability to mitigate the impacts of unpaved resource roads on surface water quality. Field studies to determine the controls on sediment production from unpaved resource roads are protracted through the requirement of several years of field monitoring to observe the representative number of natural rainfall events encompassing typical critical storms that are required to obtain conclusive results related to rainfall phenomena [Meyer, 1994]. "Access to good data is the greatest limitation to the development of sediment generation and delivery models for unsealed roads" [Fu et al., 2010]. Rainfall simulation allows for controlled, repeatable, and adaptable experiments to determine erosion and runoff characteristics in a timely manner [Meyer, 1994], and are thus useful to rapidly and efficiently study a wide spectrum of rainfall and traffic scenarios under controlled conditions. We therefore studied the controls on the amount of sediment generated from an unpaved resource road section in the Honna Watershed on Haida Gwaii, British Columbia, Canada, during different rainfall and traffic conditions using a large mobile rainfall simulator. Specifically, we examined (i) the relation between rainfall intensity and the total amount of sediment produced from the road surface, (ii) the relation between the number of loaded logging truck passages during a rainfall event and the total amount of sediment produced from the road surface, and (iii) the effect of rainfall intensity on elevated sediment concentrations in road surface runoff following a logging truck passage. Furthermore, we used a small-scale rainfall simulator to study the spatial variability in sediment production along an unpaved resource road section.

## 2. Study Site

This study was conducted in the Honna watershed, located on Graham Island, Haida Gwaii, British Columbia, Canada. The outlet of the  $\sim 52 \text{ km}^2$  watershed is located 4 km northwest of the Village of Queen Charlotte, and approximately 30 km northwest of the Community of Sandspit (Figure 1). The Honna watershed is used as the primary drinking water supply for the Village of Queen Charlotte and extends from sea level to 1000 m above sea level (asl), with a gently rolling north-south valley along the Honna River. The average slope in the watershed is 23%. The watershed contains 97 km of streams and over 90 km of unpaved resource roads, whose use depends on harvesting activities. Approximately 10 km of the unpaved Queen Charlotte Mainline Forest Road South (hereafter named the *Mainline*) was maintained and used for active hauling by logging trucks during the September–November 2009 study period. The Mainline is the primary route for off-highway logging trucks to the log sort west of the Village of Queen Charlotte and the main access route to the west coast of Graham Island for recreational vehicles. It experienced between 10 and 20 passes of loaded logging trucks daily, in addition to light vehicle traffic (i.e., cars and pickup trucks) during the September–November 2009 study period. The off-highway logging trucks had five axels with a loaded gross vehicle weight of 136,090 kg and an unloaded weight of approximately 39,000 kg [BC Ministry of Forests, 1999] (Figure 2c). In contrast, a typical loaded highway logging truck in BC has a gross vehicle weight of 63,700 kg [BC Ministry of Forests, 1999]. Roads are only graded during active hauling, generally once per month. Severe rutting and rill formation (as, for example, in Ramos-Scharrón and MacDonald [2005], Ramos-Scharrón [2012], and Thomaz et al [2014]) were not observed during the study period.

Six kilometer of the Mainline parallels the main stem of the Honna River and is located just meters from its east bank (Figure 1), resulting in a high connectivity between the Mainline and the Honna River. The average slope of this road section is 3%. A preliminary sediment yield study using the Water Quality Effectiveness Evaluation procedure [Carson et al., 2009] for all road crossings between km 3 and 10 of the Mainline and turbidity monitoring in the Honna river suggested the Mainline may have contributed between 5 and 35% of the sediment yield of the Honna River between September 2010 and August 2011 [Baird et al., 2012]. The road surface was identified as the major source of road generated sediment along the Mainline; ditches, cut slopes, and fill slopes along the Mainline are generally well vegetated and are less erodible than the road surface [Baird et al., 2012].

The Honna watershed is located within the hypermaritime subzone of the Coastal Western Hemlock and Mountain Hemlock biogeoclimatic zones [Meidinger and Pojar, 1991], one of Canada's wettest and most

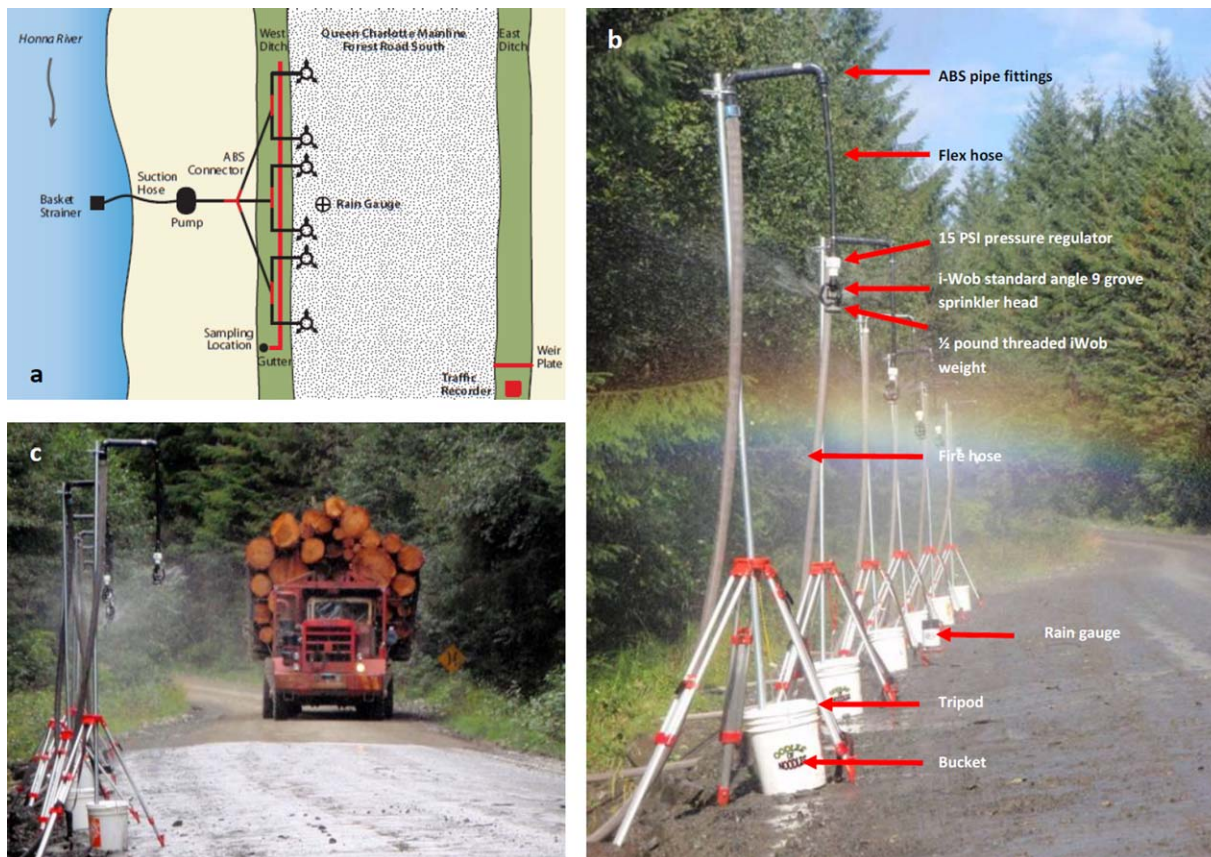




**Figure 1.** Location of the Honna Watershed, Village of Queen Charlotte, the rain gauges, and the small-scale and large-scale rainfall simulation experiments.

productive forest regions [Egan *et al.*, 1999]. Long-term climate data are not available for the Honna Watershed, but climate normals are expected to follow the same trends as Sandspit (6 m asl), except that the Honna Watershed receives more precipitation due to orographic effects. The daily average temperature in Sandspit is 8.3°C, and annual average precipitation is 1398 mm, with on average 222 days of detectable (>0.2 mm) precipitation per year [Environment Canada, 2013]. The average precipitation between 1 September and 30 November in Sandspit is 467 mm [Environment Canada, 2013]. Precipitation was measured during this study in a wetland near km 10 of the Mainline (Grapple 10) at 150 m asl and near Stanley Lake at 250 m asl (Figure 1). Total precipitation during the 1 September 2009 to 30 November 2009 study period was 769 mm at Grapple 10 and 1211 mm at Stanley Lake. The data given in the remainder of the text are from the Grapple 10 rain gauge, as this site is located closest to the rainfall simulation sites (Figure 1).

The watershed has a siltstone and mudstone dominated lithology. The section of the Mainline paralleling the main stem of the Honna River runs through Skidegate Formation mudstone and shale [Haggart, 2004]. The road was resurfaced in 2007 with a siltstone ballast to a depth of 40 cm. The surface road material has a sandy loam texture (55% sand, 35% silt, 15% clay). Siltstone and mudstone are a relatively unstable road bed and surface materials, which was confirmed by field observations of rapidly degrading ballast on the Mainline; surface material can in places be crushed by hand. Aggregate material more resistant to erosion, however, is not readily available on the Island. Observations also showed the ballast being pushed into the



**Figure 2.** (a) Setup for the large-scale rainfall simulation experiments, (b) oblique view of the large-scale sprinkler setup, and (c) loaded logging truck passage during a large-scale rainfall simulation experiment.

road bed with fine sediments likely being forced upward, similar to observations in other studies [e.g., Reid and Dunne, 1984].

### 3. Methods

#### 3.1. Large-Scale Rainfall Simulations

Twenty three large-scale rainfall simulation experiments were conducted on a 30 m long section of the Mainline near km 8 between 30 August 2009 and 23 October 2009 (Figure 1 and Table 1). This location was selected because it is representative of road surfaces with the potential to contribute sediment to the Honna River [Bruce and Chatwin, 1987, 1988; Baird et al., 2012].

The large mobile rainfall simulator consisted of six i-Wob® nozzles (Senninger Irrigation Ltd., Clermont, FL, USA), tripods, hose, pipe, and a pump (Figure 2b). The i-Wob nozzle is an inverted rotating-plate irrigation nozzle, which allows low intensity spraying, while still maintaining a large drop size. Water was drawn directly from the Honna River through 50 mm semirigid suction hose with a basket strainer encased in a fiberglass bonded filter sleeve (uncompressed thickness of 10 mm) using a Honda WH20X high-pressure water pump. Water was then carried through 38 mm diameter canvas fire hose to the sprinkler heads, which were connected to the fire hose using 38 mm ABS (Acrylonitrile Butadiene Styrene) fittings (Figure 2a). Individual hose sections were also connected using 38 mm diameter ABS fittings. Sprinkler heads, consisting of a 0.6 m section of reinforced flexible tubing, a 100 kPa pressure regulator, a standard nine groove i-Wob sprinkler head, and an 0.2 kg i-Wob threaded weight, were elevated 3 m above the road surface using rigid metal piping and surveying tripods, counter balanced by 40 L buckets filled with water (Figure 2b). Three different nozzle apertures were used within the sprinkler head to obtain different precipitation intensities (Table 1). The nozzles were selected based on the 2 (nozzle 6) and 10–15 (nozzle 11) year return

**Table 1.** Overview of the Large-Scale Rainfall Simulation Experiments

| Experiment                          | Duration (h:mm) | Traffic | Date        | Temporal Uniformity Coefficient (%) | Sprinkler Intensity (mm/h) | Return Interval (Years) | Runoff Ratio <sup>a</sup> (-) |
|-------------------------------------|-----------------|---------|-------------|-------------------------------------|----------------------------|-------------------------|-------------------------------|
| <i>Nozzle 6 (Low Intensity)</i>     |                 |         |             |                                     |                            |                         |                               |
| L1                                  | 2:30            | No      | 30 Aug 2009 | N/A                                 | 6.5 <sup>b</sup>           | 1.5                     | 0.8                           |
| L2                                  | 2:56            | Yes     | 31 Aug 2009 | 87                                  | 7.3                        | 2.0                     | 0.7                           |
| L3                                  | 5:00            | Yes     | 1 Sep 2009  | N/A                                 | 6.5 <sup>b</sup>           | 2.5                     | 0.9                           |
| L4                                  | 3:00            | Yes     | 3 Sep 2009  | N/A                                 | 6.5 <sup>b</sup>           | 2.0                     | 0.8                           |
| L5                                  | 5:00            | No      | 6 Sep 2009  | 79                                  | 4.7                        | 1.5                     | 1.2                           |
| L6                                  | 2:05            | No      | 7 Sep 2009  | N/A                                 | 6.5 <sup>b</sup>           | 1.5                     | 0.8                           |
| L7                                  | 3:00            | Yes     | 9 Sep 2009  | N/A                                 | 6.5 <sup>b</sup>           | 2.0                     | 0.8                           |
| L8                                  | 5:00            | Yes     | 14 Sep 2009 | 80                                  | 6.5                        | 2.5                     | 0.9                           |
| L21                                 | 4:00            | No      | 8 Oct 2009  | 87                                  | 7.3                        | 3.0                     | 0.9                           |
| L22                                 | 3:00            | Yes     | 19 Oct 2009 | N/A                                 | 6.5 <sup>b</sup>           | 2.0                     | 0.9                           |
| <i>Nozzle 11 (Medium Intensity)</i> |                 |         |             |                                     |                            |                         |                               |
| L9                                  | 2:30            | Yes     | 17 Sep 2009 | 91                                  | 14.9                       | 15                      | 1.1                           |
| L10                                 | 4:00            | No      | 19 Sep 2009 | 91                                  | 16.6                       | >15                     | 1.0                           |
| L11                                 | 4:00            | Yes     | 22 Sep 2009 | 93                                  | 16.7                       | >15                     | 1.0                           |
| L12                                 | 2:30            | Yes     | 24 Sep 2009 | 88                                  | 11.8                       | 10                      | 1.4                           |
| L13                                 | 2:00            | No      | 26 Sep 2009 | 91                                  | 17.4                       | >15                     | 0.9                           |
| L14                                 | 2:30            | Yes     | 28 Sep 2009 | 90                                  | 14.7                       | 15                      | 1.1                           |
| L15                                 | 2:30            | Yes     | 29 Sep 2009 | 89                                  | 14.9                       | 15                      | 1.1                           |
| L20                                 | 3:00            | No      | 7 Oct 2009  | 91                                  | 18.1                       | >15                     | 0.9                           |
| <i>Nozzle 22 (High Intensity)</i>   |                 |         |             |                                     |                            |                         |                               |
| L16                                 | 1:28            | Yes     | 1 Oct 2009  | 93                                  | 52.2                       | >15                     | 1.0                           |
| L17                                 | 1:15            | Yes     | 2 Oct 2009  | 92                                  | 40.4                       | >15                     | 1.1                           |
| L18                                 | 2:00            | No      | 3 Oct 2009  | 86                                  | 40.5                       | >15                     | 1.1                           |
| L19                                 | 2:00            | No      | 6 Oct 2009  | 95                                  | 39.9                       | >15                     | 1.1                           |
| L23                                 | 2:00            | Yes     | 23 Oct 2009 | 85                                  | 50.0                       | >15                     | 0.9                           |

<sup>a</sup>Runoff ratios >1 are due to uncertainties in determining the total runoff from the gutter and the area that drained to the gutter.

<sup>b</sup>Assigned average value.

interval storms in the Honna watershed, which were determined using the available precipitation data (June 1990 to April 2002) for the Honna Watershed from the Ministry of Forests and Range Wildfire Management Branch (Victoria, BC). The rain gauge in the Honna Watershed was moved in 2002 and more recent data are not available. The available data have frequent gaps, especially in fall and winter, but comparison with the Sandpit intensity-duration-frequency curves and the intensity-duration-frequency map for southern Graham Island [Murray, 1964] showed there were only small differences between the curves, with the intensities for the Honna watershed being higher than for Sandspit. In order to determine the response to extreme rainfall intensity events, experiments were also done with a third nozzle (nozzle 22). Experiments with nozzle 6 are designated *low intensity* experiments. Experiments with nozzle 11 and 22 are designated *medium* and *high intensity experiments*, respectively, in the remainder of the text.

Sprinkler rainfall intensity was measured at 5 min intervals throughout each experiment using an Onset RG3-M 0.2 mm tipping bucket rain gauge (Onset, Bourne MA, USA). Due to equipment failure, sprinkler rainfall intensity data are not available for experiments 1, 3, 4, 6, 7, and 22. These experiments with nozzle 6 were assigned the mean intensity of the other experiments using nozzle 6 (6.5 mm/h). The temporal Christiansen uniformity coefficient ( $CU = 1 - (D/M)$ , where  $D$  is the average absolute deviation of the rainfall intensity and  $M$  is the average rainfall intensity) [Christiansen, 1942] was greater than 70% for all experiments for which precipitation data were available, indicating the rainfall simulator produced precipitation of reasonably constant intensity.

In situ measurements of the spatial variability in sprinkler rainfall intensity were limited by frequent traffic through the study site. Spatial uniformity was assessed during one low intensity experiment using eleven small (63 mm diameter) funnel rain gauges. Spatial variability around a single nozzle was assessed more extensively at a nonroad location following the experiments. Results of these measurements showed uniform rainfall intensity (spatial Christiansen uniformity coefficient [Christiansen, 1942] of 100%) between 0 and 4.25 m from the nozzle and a sharp decline in intensity thereafter. The maximum distance wetted by the sprinklers was ~5 m for nozzles 6 and 11 and ~6.5 m for nozzle 22.

To assess the comparability of the kinetic energy of the rainfall simulator and natural precipitation in the area, the drop size distribution was measured for both natural and simulated rainfall using the oil method [Eigel and Moore, 1983]. Simulated drop sizes ranged between 0.1–3.3, 0.1–7.0, and 0.2–6.0 mm at precipitation intensities of 7.3,



14.8, and 40.4 mm/h, respectively. The median drop size was 0.9, 0.9, and 1.1 mm at precipitation intensities of 7.3, 14.8, and 40.4 mm/h, respectively. These drop sizes agree reasonably well with the drop size for natural precipitation at the study site (range: 0.2–2.3 mm, median 0.7 mm for a 2.6 mm/h event), as well as the range from near zero to approximately 7 mm and a median between 1 and 3 mm, depending on intensity given by Meyer [1994] and the median drop size of 0.1–1.5 mm for orographic precipitation given by Blanchard [1953].

To collect road runoff, a 30 m long, 100 mm wide metal gutter was buried next to the road shoulder along the west side of the road in August 2009 (Figure 2a). Blue dye added to runoff water during the experiments indicated all runoff from the western half of the road was caught by the gutter. The gutter was installed carefully to minimize soil disturbance during installation. Natural rainfall events and testing of the large-scale rainfall simulator allowed the redevelopment of an armor layer on the material that was disturbed during installation. There were no visible differences between the material that sealed the gutter and the surrounding surface of the shoulder prior to the first rainfall simulation experiment. Gutter outflow rates were determined from the time it took to fill a 8.3 L container and generally increased logarithmically from the start of an experiment to steady state. Grab samples were taken at the end of the gutter throughout the experiments. The sampling interval changed during the experiments; samples were taken more frequently at the start of the experiment and during truck passages. The number of samples taken during the 1–5 h experiments ranged from 15 to 37. The samples were passed through 1.6  $\mu$ m glass microfiber filters, dried at 200°C for 20 min and weighed to determine the sediment concentration.

A 60° v-notch weir was installed in the east ditch opposite the most southern sprinkler head (Figure 2a). The ditch only flowed during large or prolonged rainfall events. Weir grab samples were collected concurrently with gutter samples when possible to compare water flowing in the ditch to that collected in the gutter. The samples were analyzed similar to the grab samples from the gutter.

TRAFx vehicle counters (TRAFx Research Ltd., Canmore, AB, Canada) were installed at the southern end of the large-scale rainfall simulation experiment site and near km 3 on the Mainline to keep track of the number of vehicles passing during and prior to the rainfall simulation experiments. Individual vehicle passages were also recorded manually during the large-scale experiments and when possible their speed was estimated by timing the passage between two points a known distance apart. Vehicles were classified as loaded off-highway logging trucks (hereafter named *loaded trucks*), empty off-highway logging trucks (hereafter named *unloaded trucks*), other large industrial vehicles (hereafter named *work trucks*), or personal vehicles (including pickup trucks). Personal vehicles were narrow enough to only influence the eastern half of the road surface and did not affect runoff entering the gutter. Logging trucks and work trucks were wide enough to have at least one tire track on the western half of the road, influencing runoff to the gutter.

### 3.2. Small-Scale Rainfall Simulations

Seven small-scale rainfall simulation experiments were conducted between 20 and 22 November 2009 to determine the spatial variability in sediment generation from the road surface; five of the small-scale rainfall simulation experiments were conducted between km 3 and km 7 of the Mainline, while two additional simulations were conducted along a well-maintained spur road that is frequently used by personal vehicles and occasionally by work trucks (Figure 1). The locations of the small-scale rainfall simulation experiments were chosen to be representative of the kilometer section in which they were located and were restricted to locations south of km 7 to avoid rainfall simulation on frozen or snow covered road surfaces.

A single i-WOB sprinkler head was used for the small-scale experiments (Table 2) with water supplied from a 300 L tank, transported in the back of a pickup truck. A 1 m diameter section of road adjacent to the sprinkler head was isolated using a 10 cm high thin metal barrier. The metal barrier was carefully placed on the road surface, and sealed with a clay mixture around the outside of the barrier to prevent inflow from areas outside the barrier and leakage of surface runoff from within the barrier. A 2.5 cm diameter plastic hose installed at the lowest point, allowed the collection of surface runoff. Outflow rates were determined by measuring the time required to collect samples of a known volume from the outflow hose. The samples were analyzed similar to the samples from the large-scale rainfall simulation experiments.

### 3.3. Data Analysis

To convert sediment concentrations into a mass of sediment, point sediment concentration measurements were multiplied by the outflow rate at that time and the time period half way between the previous and



**Table 2.** Overview of the Small-Scale Rainfall Simulation Experiments

| Experiment | Duration (h:mm) | Slope (%) | Date        | Temporal Uniformity Coefficient (%) | Sprinkler Intensity (mm/h) | Return Interval (Years) | Total Mass (g) | Measured Peak Sediment Concentration (g/L) |
|------------|-----------------|-----------|-------------|-------------------------------------|----------------------------|-------------------------|----------------|--|
| S1         | 0:18            | 3         | 20 Nov 2009 | 80                                  | 6.6                        | 1.0                     | 2.5            | 2.5  |
| S2         | 0:56            | 2         | 20 Nov 2009 | 70                                  | 4.2                        | <1                      | 3.5            | 5.1  |
| S3         | 0:39            | 2         | 21 Nov 2009 | 87                                  | 4.9                        | <1                      | 1.4            | 1.4  |
| S4         | 0:54            | 3         | 21 Nov 2009 | 78                                  | 5.3                        | 1.0                     | 4.5            | 4.5  |
| S5         | 0:44            | 3         | 21 Nov 2009 | 85                                  | 7.9                        | 1.5                     | 11.4           | 10.5                                       |
| S6         | 0:36            | 2         | 22 Nov 2009 | 88                                  | 8.6                        | 1.5                     | 1.2            | 2.5  |
| S7         | 0:55            | 3         | 22 Nov 2009 | 86                                  | 19.5                       | >10                     | 7.3            | 5.0  |

following measurement points. The maximum expected error in the sediment concentrations and the calculated mass of sediment were estimated through an error propagation calculation using the precision of the balance (0.02 g), the estimated error in measuring the volume in the container (2 mL), and the estimated error in the time to fill the container (2 s). The standard deviation of the measured steady state flow rates for each individual trial was used to represent the error in the steady flow rate. For the first 30 (nozzle 6 experiments), 11 (nozzle 11 experiments), or 5 (nozzle 22 experiments) min during an experiment when the flow rate was increasing, a value of 0.1 times the flow rate was used to represent the error in the measured outflow rate.

The 3, 5, and 10 day normalized antecedent precipitation index (API) values were calculated for the beginning of each experiment based on the precipitation data collected 2 km north of the large-scale rainfall simulation site at Grapple 10 and the rainfall during previous simulations:

$$API_n = \sum_{i=1}^n \left( \frac{P_i}{i} \right) \quad (1)$$

where  $P_i$  is the precipitation in the  $i$ th day before the experiment and  $n$  is 3, 5, or 10.

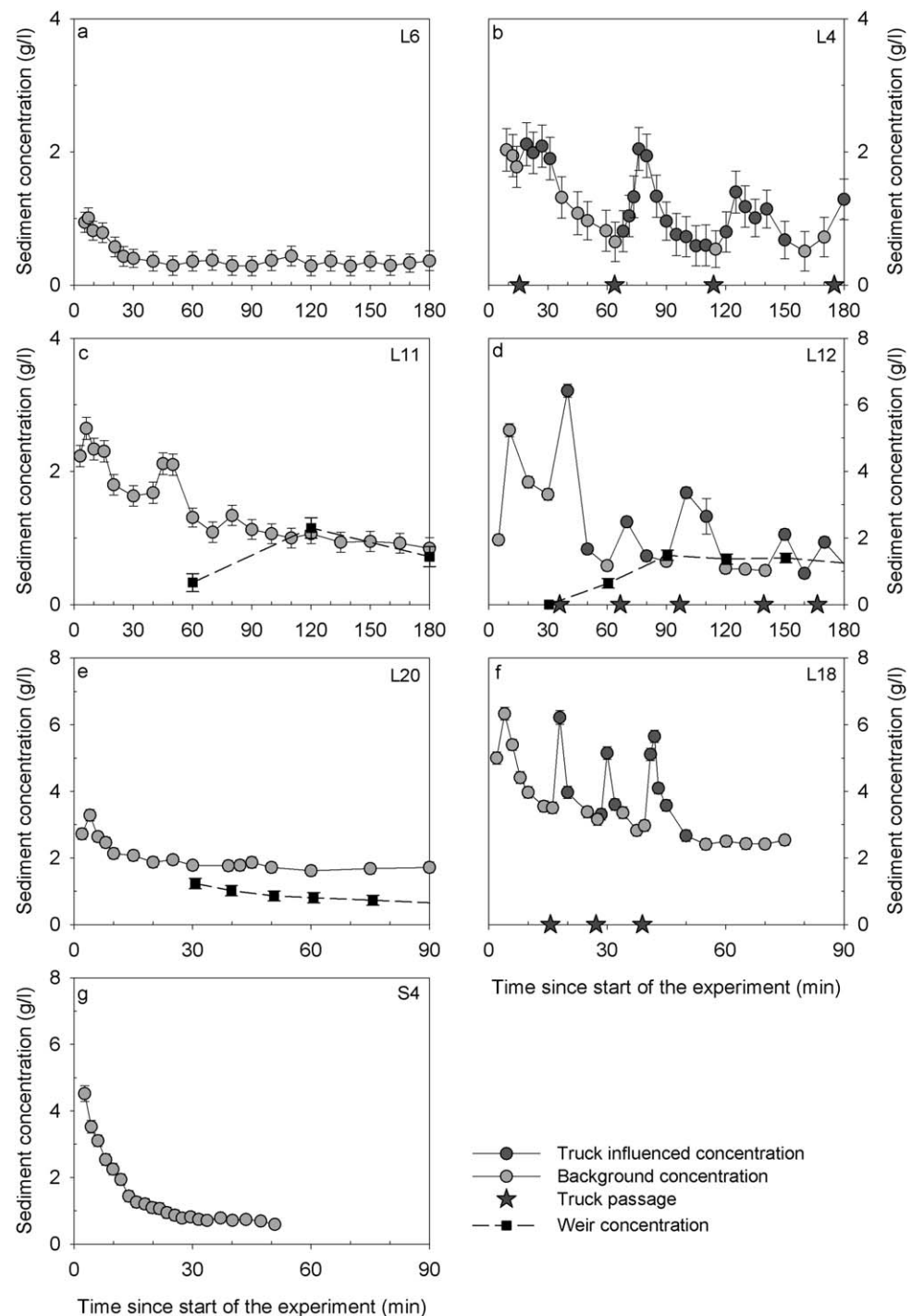
The number of loaded and unloaded trucks, work trucks, personal vehicles, and total number of vehicles passing through the site during the 1, 2, 3, 6, and 24 h period before the start of each large-scale experiment were calculated using the data from the traffic recorders. Data from the traffic recorder at km 8 were used for the large-scale rainfall simulation experiments; the data from the traffic recorder at km 3 were used for all small-scale experiments. For experiments 1–3 and 6–9 data on antecedent traffic is missing.

Correlation analysis was used to determine the relations between the mass of sediment and precipitation amount, precipitation intensity, experiment duration, total number of truck passages, truck speed, antecedent precipitation index, and antecedent traffic conditions. Stepwise multiple linear regression was used to identify the main factors controlling the amount of sediment generated from the road surface during the experiments. ANOVA and simple  $t$ -tests were used to determine whether the amount of sediment produced from the road surface during the experiments with the different nozzles (rainfall intensities) were statistically different. Similar tests were done to determine the difference in the total amount of sediment generated during experiments with and without loaded logging truck passages. A significance level of 0.05 was used for all analyses.

## 4. Results and Discussion

### 4.1. Large-Scale Rainfall Simulation Results

Sediment concentrations in the gutter increased at the start of the experiments and then decreased to a steady state concentration for the experiments without traffic (Figures 3a, 3c, and 3e). Peak sediment concentrations were reached quickly after the start of the experiments (between 6–16, 5–13, and 4–5 min after the start of the experiment for the low, medium, and high precipitation intensity experiments, respectively). The measured peak sediment concentrations were highly variable and ranged between 0.6–4.6, 0.9–15.0, and 3.3–10.7 g/L for the low, medium, and high intensity experiments, respectively. The steady state



**Figure 3.** Sediment concentrations during (a and b) a low intensity experiment, (c and d) a medium intensity experiment, (e and f) a high intensity experiment, and (g) a small-scale experiment without loaded truck passages (Figures 3a, 3c, 3e, and 3g) and with loaded truck passages (Figures 3b, 3d, and 3f). The times that a loaded truck passed the site are indicated by a star. Error bars represent the estimated maximum error in the concentration measurements.

sediment concentrations ranged between 0.1–1.0, 0.3–1.8, and 1.6–4.1 g/L for the low, medium, and high intensity experiments, respectively (Table 3) and were related to the rainfall intensity ( $R^2 = 0.77$ ). These results are similar to the findings of Arnáez *et al.* [2004] and Ziegler *et al.* [2001b], who reported greatly reduced sediment concentrations in runoff after the first few minutes of precipitation. The relation between sediment concentrations and gutter outflow during experiments without loaded truck passages showed

**Table 3.** Overview of the Calculated Background (Nontruck Influenced) Sediment Mass and Mass From Traffic for the Large-Scale Rainfall Simulation Experiments<sup>a</sup>

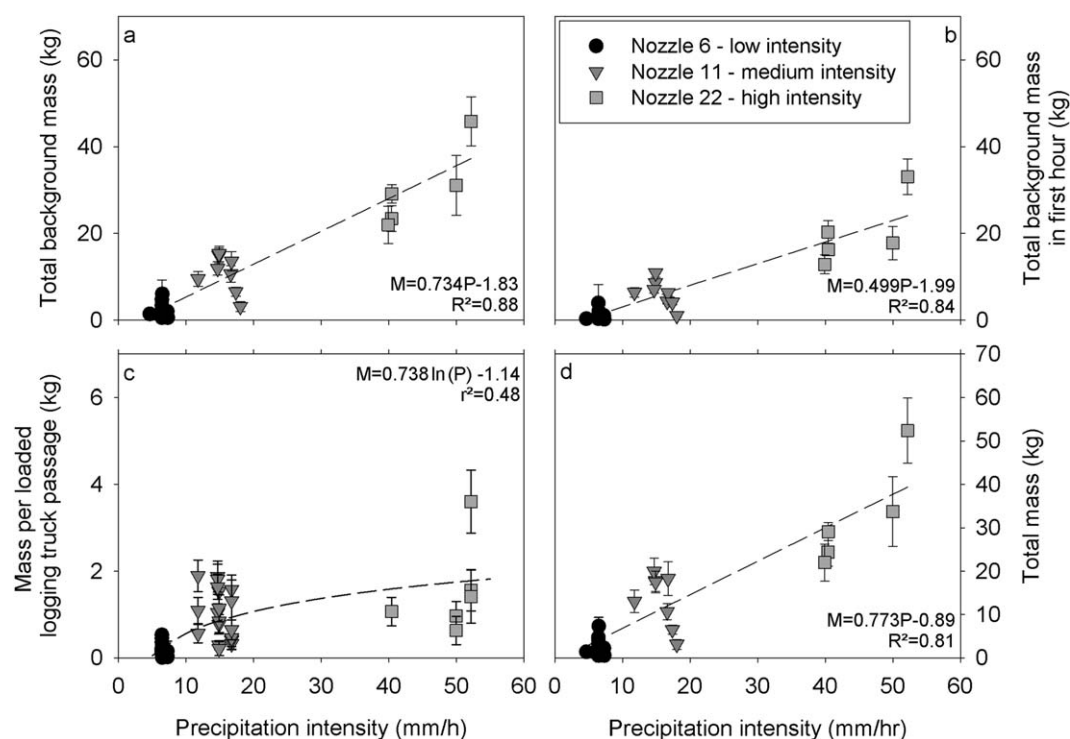
| Experiment                          | Number of Loaded Trucks | Total Mass (kg) | Total Background Mass (kg) | % of Total Mass Directly Caused by Traffic | Average Mass Per Truck (kg) | Measured Peak Concentration (g/L) | Steady State Concentration (g/L) |
|-------------------------------------|-------------------------|-----------------|----------------------------|--|-----------------------------|-----------------------------------|----------------------------------|
| <i>Nozzle 6 (Low Intensity)</i>     |                         |                 |                            |  |                             |                                   |                                  |
| L1                                  | 0                       | 4.8             | 4.8                        |  |                             |                                   | 0.6                              |
| L2                                  | 4                       | 2.3             | 2.0                        | 11   | 0.06                        | 3.6                               | 0.6                              |
| L3                                  | 9                       | 4.4             | 3.3                        | 25   | 0.12                        | 1.5                               | 0.8                              |
| L4                                  | 4                       | 2.8             | 2.0                        | 26   | 0.18                        | 2.0                               | 0.6                              |
| L5                                  | 0                       | 1.4             | 1.4                        |  |                             | 0.8                               | 0.3                              |
| L6                                  | 0                       | 0.6             | 0.6                        |  |                             | 0.9                               | 0.3                              |
| L7                                  | 2                       | 2.3             | 1.8                        | 24   | 0.28                        | 3.5                               | 0.5                              |
| L8                                  | 8                       | 7.3             | 6.0                        | 17   | 0.16                        | 4.6                               | 1.0                              |
| L21                                 | 0                       | 0.6             | 0.6                        |  |                             | 0.6                               | 0.1                              |
| L22                                 | 6                       | 3.4             | 1.2                        | 64   | 0.36                        | 0.7                               | 0.6                              |
| <i>Nozzle 11 (Medium Intensity)</i> |                         |                 |                            |  |                             |                                   |                                  |
| L9                                  | 4                       | 17.8            | 14.9                       | 16   | 0.72                        | 11.1                              | 1.8                              |
| L10                                 | 0                       | 10.7            | 10.7                       |  |                             | 2.6                               | 0.8                              |
| L11                                 | 6                       | 18.3            | 13.5                       | 26   | 0.79                        | 5.2                               | 0.9                              |
| L12                                 | 3                       | 13.0            | 9.5                        | 27   | 1.18                        | 6.1                               | 0.9                              |
| L13                                 | 0                       | 6.5             | 6.5                        |  |                             | 3.8                               | 1.0                              |
| L14                                 | 5                       | 19.9            | 11.9                       | 40   | 1.60                        | 7.6                               | 1.3                              |
| L15                                 | 3                       | 17.5            | 15.3                       | 13   | 0.74                        | 15.0                              | 1.0                              |
| L20                                 | 0                       | 3.1             | 3.1                        |  |                             | 0.9                               | 0.3                              |
| <i>Nozzle 22 (High Intensity)</i>   |                         |                 |                            |  |                             |                                   |                                  |
| L16                                 | 3                       | 52.4            | 45.8                       | 13   | 2.19                        | 10.7                              | 4.1                              |
| L17                                 | 1                       | 24.5            | 23.4                       | 4  | 1.07                        | 6.3                               | 2.5                              |
| L18                                 | 0                       | 29.1            | 29.1                       |  |                             | 5.2                               | 2.2                              |
| L19                                 | 0                       | 22.0            | 22.0                       |  |                             | 3.3                               | 1.6                              |
| L23                                 | 2                       | 33.8            | 31.1                       | 34   | 1.36                        | 7.9                               | 2.3                              |

<sup>a</sup>See Table 1 for additional information about the date, duration, and rainfall intensity during the experiments.

clockwise hysteresis (i.e., sediment concentrations peaking before the flow). This suggests sediment transport from the road surface is a supply-limited system (rather than transport-limited system), where the amount of sediment available for transport is less than the transport capacity of road surface runoff and the available loose sediment is quickly flushed from the road bed during the first minutes of a rainfall event (i.e., the first flush effect).

During experiments with loaded logging truck passages, a similar peak sediment concentration and decline to steady state concentration were observed, except that sediment concentrations also increased after the passage of a loaded logging truck and then declined again (Figures 3b, 3d, and 3f). Visual inspection of the sediment concentrations in the gutter outflow revealed that following the passage of a loaded truck, it took approximately 5 min for the elevated concentrations in the gutter to increase and an additional 30 min for the sediment concentrations to return to background levels during low intensity rainfall simulation experiments (Figure 3b). During the medium intensity experiments it took on average 3 min for a loaded truck passage related sediment pulse to reach the outflow and another 17 min for sediment concentrations to return to background levels (Figure 3d). During the high intensity experiments, it took 1 min for the sediment concentrations to increase after a loaded truck passage and on average 14 min for the sediment concentrations to return to background levels (Figure 3f). These results are similar to the results of *Luce and Black* [2001] and *Ziegler et al.* [2001b] who showed that traffic can lead to increases in sediment concentrations that last for tens of minutes.

Sediment concentrations that were not directly affected by the passage of loaded trucks are termed *background concentrations* and were estimated for experiments with truck passages by fitting a trend line through the data points that were not directly influenced by the passage of a loaded truck. For the low intensity (nozzle 6) experiments, samples collected between 5 and 35 min after the passage of a loaded truck were excluded from the concentration time series and the power trend line was fit through the remaining data starting ~10 min after the start of the experiment. A power trend line was chosen over an exponential trend line because of the better fit for the majority of the experiments. For the medium intensity (nozzle 11) experiments, samples between 3 and 20 min after the passage of a loaded truck were excluded and the trend line was fitted through the remaining data points occurring at least 10 min into the experiment. For high intensity (nozzle 22) experiments, samples between 1 and 15 min after the passage of



**Figure 4.** The relation between precipitation intensity and (a) total background (nontruck influenced) sediment mass, (b) first hour background sediment mass, (c) sediment mass per loaded truck passage, (d) total sediment mass for the large-scale rainfall simulation experiments. The regression lines and equations are shown as well, where  $M$  is the mass of sediment and  $P$  is the precipitation intensity.

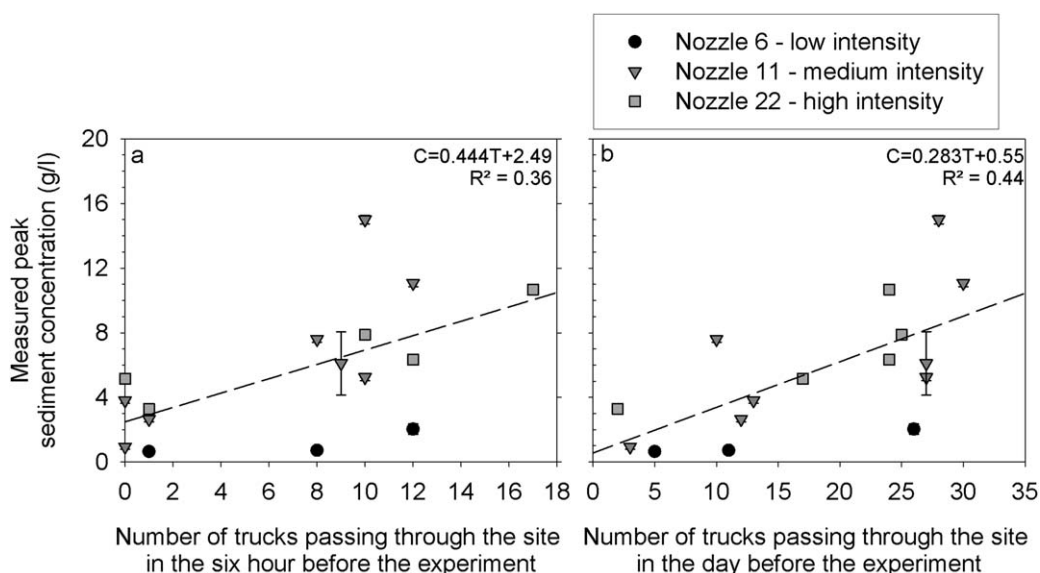
a loaded truck were removed and the trend line was fitted through all remaining data points at least 2 min into the experiment. The concentration increase due to a loaded truck passage was calculated as the difference between the measured concentration and the estimated background concentrations from the aforementioned trend lines. For loaded trucks that passed in succession, i.e., a second loaded truck passed before the influence of the previous loaded truck had diminished, the total amount of sediment generated by the passage of the loaded trucks was summed and then divided by the total number of loaded trucks that had passed.

#### 4.1.1. Controls on Sediment Production in the Absence of Loaded Logging Trucks

There was a positive linear relation between precipitation intensity and the mass of background sediment generated during the first hour of each experiment (Figure 4b), as well as between precipitation intensity and the mass of background sediment generated during the entire experiment (Figure 4a). There was also a positive linear relation between total precipitation and the mass of background sediment generated in the first hour or the entire experiment. The  $R^2$  of the relation between precipitation intensity and background sediment mass was 0.88 and 0.84 for the entire experiment and the first hour, respectively. The  $R^2$  of the relation between precipitation amount and background sediment mass was 0.64 and 0.81 for the entire experiment and the first hour, respectively. The  $R^2$  of the relation between precipitation intensity and precipitation amount was 0.76 for the large-scale experiments. The intercepts of the relations between precipitation intensity and background sediment mass could suggest a threshold precipitation intensity is required to initiate sediment transport off the road but they were not significantly different from zero ( $p = 0.20$  and  $0.09$  for the intercept of the relation between background sediment mass and precipitation intensity for the entire experiment and the first hour of the experiment, respectively).

These results are in agreement with the results of Amman [2004], who found for a site in Oregon that variations in suspended sediment concentrations in resource road runoff during rain events were most strongly related to precipitation intensity when it was time lagged to account for sediment transport. However, these results are contradictory to the findings of Croke *et al.* [2006], who found no significant relation



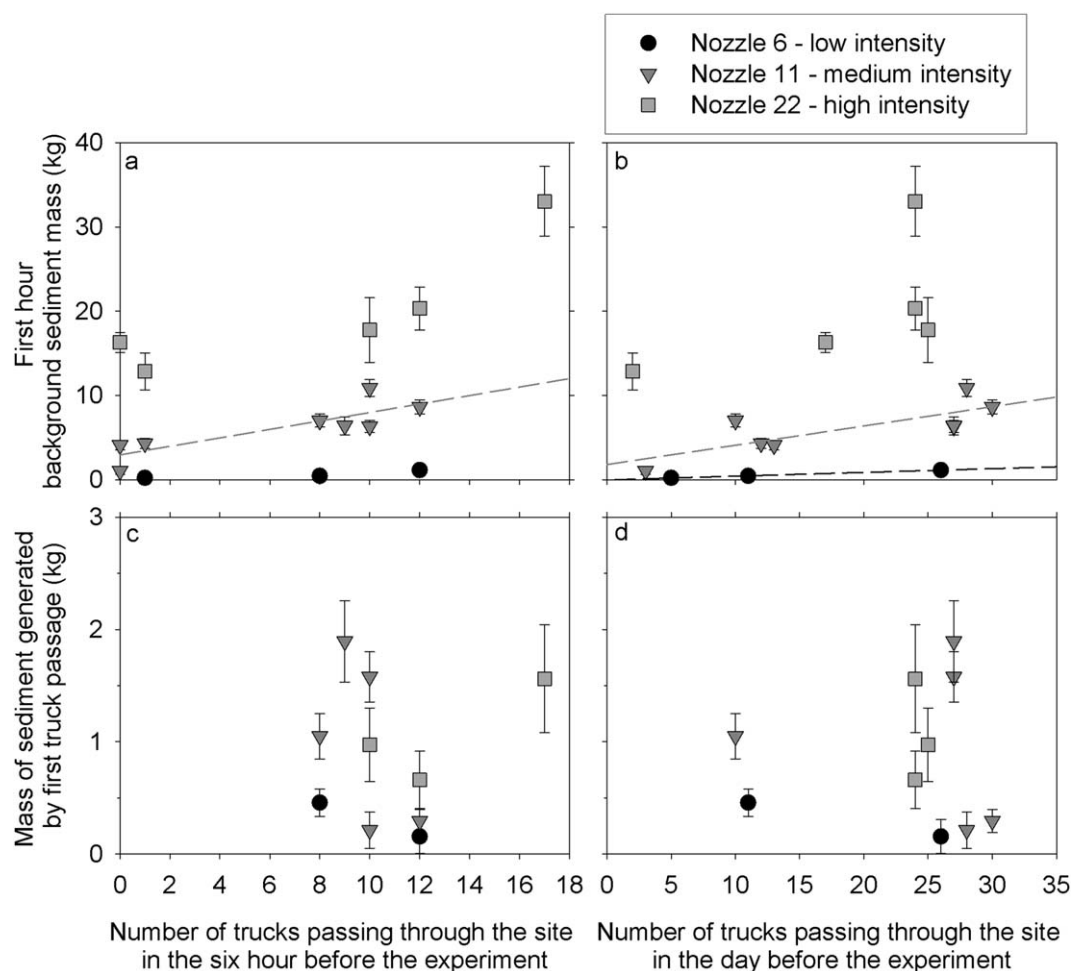


**Figure 5.** The relation between the number of trucks (loaded, unloaded, and work trucks) passing through the site in the (a) 6 h and (b) 24 h prior to the start of the experiment and the peak sediment concentration measured during the experiment. The regression lines and equations are shown as well, where  $C$  is the measured peak sediment concentration and  $T$  is the number of trucks.

between sediment concentrations in road surface runoff and rainfall intensity for a site in southeastern New South Wales, Australia but their research site only had two rainfall intensities applied (75 and 110 mm/h) and the road surface had more competent material.

There was no relation between experiment duration (i.e., rainfall event duration) and the total background sediment mass generated from the road surface for the large-scale rainfall simulation experiments (Table 3). This suggests that for the rainfall durations in this study (1–5 h), the initial sediment pulse dominates the total mass of background sediment generated from the road. The peak sediment concentrations were related to the antecedent traffic conditions, in particular the number of trucks passing through the site in the 2, 3, 6, and 24 h prior to the experiment (Figure 5). However, the relation between the background mass of sediment generated from the road and the number of trucks (loaded and unloaded trucks and work trucks) or the total number of vehicles passing through the site in the previous 1, 2, 3, 6, or 24 h periods were not consistently significant, except for the medium intensity experiments (Figures 6a and 6b). For example,  $p$  was 0.38, 0.28, and 0.02 for the relation between background sediment mass and the number of trucks passing through the site in the 3, 6, and 24 h prior to the start of the experiment, respectively, for the nozzle 6 experiments;  $p$  was 0.20, 0.06, and 0.28 for the relation between background sediment mass and the number of trucks passing through the site in the 3, 6, and 24 h prior to the start of the experiment, respectively, for the nozzle 22 experiments. The relative small number of experiments for which antecedent traffic data were available ( $n = 3, 8$ , and 5 for the nozzle 6, 11, and 22 experiments, respectively) may have caused the linear relations between antecedent traffic and background sediment mass to be not consistently significant for the low and high intensity experiments. The slopes of the relations between antecedent traffic and total background sediment mass may point to a higher sensitivity to antecedent traffic at higher rainfall intensities (Figures 6a and 6b) and the need for additional experiments to confirm this. These (visual) relations between antecedent traffic, peak sediment concentrations, and background sediment mass are in agreement with the findings of *Bilby et al.* [1989], who showed the total number of axles since the last storm influenced sediment concentrations in ditch flow for normal traffic conditions. *Ziegler et al.* [2001b] showed that the sediment generated by truck and motorcycle passes during an extended dry period prior to an event was quickly flushed from the road and this initial flush was absent for an event during a wet period because the event on the previous day had removed most of the loose material generated by the motorcycle and pickup truck passages. A first flush was observed for all experiments in this study, even for experiments with high antecedent precipitation.

There was no significant relation between the 3, 5, or 10 day API and the total amount of background sediment generated from the road during an experiment or the first hour of an experiment ( $p$  values ranging

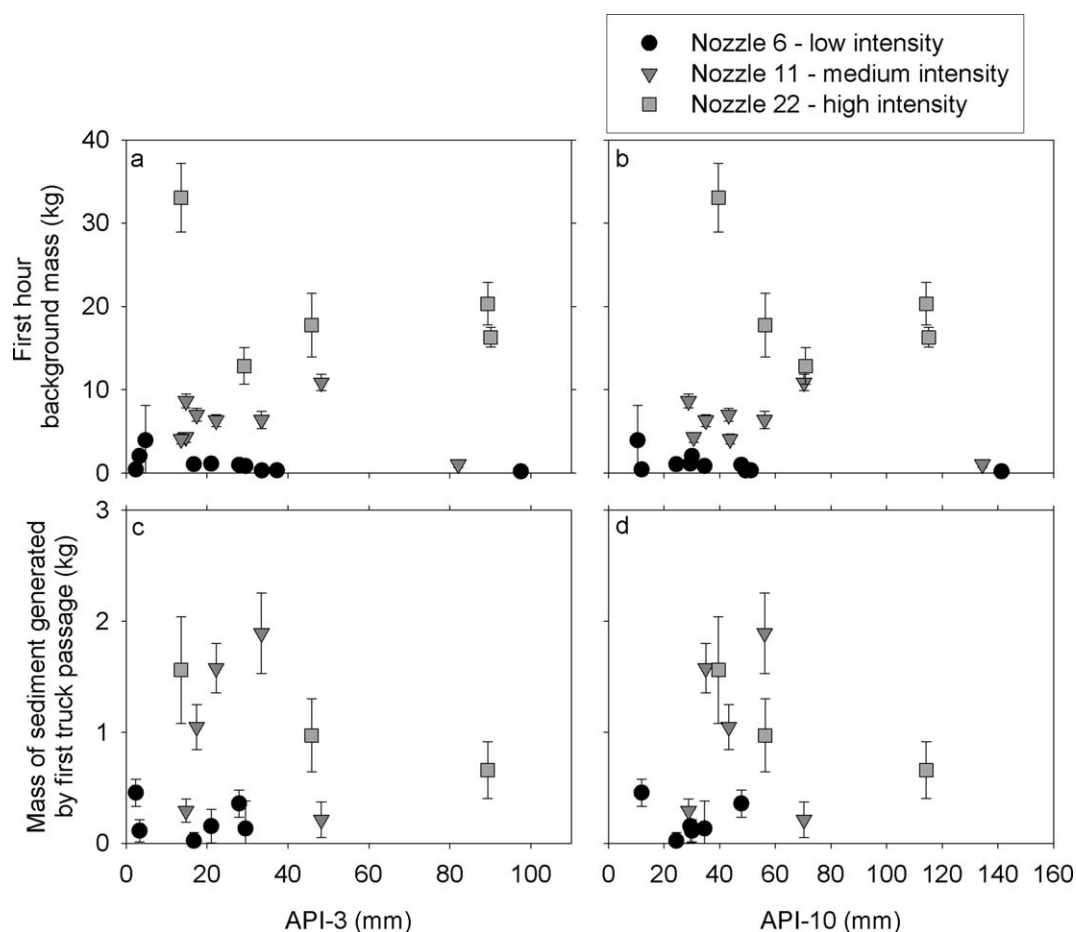


**Figure 6.** The relation between the number of trucks (loaded, unloaded, and work trucks) passing through the site in the (a and c) 6 h and (b and d) 24 h prior to the start of the experiment and background (nontruck influenced) sediment mass in the first hour of the experiment (Figures 6a and 6b) and the mass of sediment generated by the first loaded truck passage (Figures 6c and 6d). The dashed lines represent statistically significant linear regression lines. The regression equation for the relation between the number of trucks passing in the 6 h prior to the experiments and the first hour background sediment mass is  $M = 0.503T + 2.94$  ( $R^2 = 0.72$ ), where  $M$  is the sediment mass and  $T$  is the number of trucks. The regression equations for the relation between the number of trucks passing in the day prior to the experiments and the first hour background sediment mass is  $M = 0.044T - 0.03$  ( $R^2 = 0.99$ ) and  $M = 0.229T + 1.78$  ( $R^2 = 0.63$ ) for the nozzle 6 and nozzle 11 experiments, respectively.

between 0.1 and 0.5; Figures 7a and 7b). These results suggest that antecedent moisture conditions had no significant effect on sediment generation from this resource road, although none of the experiments were done after an extended dry period and the limited number of experiments reduces the strength of any relation. Antecedent precipitation was also not significantly related to the runoff ratio, suggesting runoff occurred regardless of antecedent wetness conditions. The runoff ratio was high for all experiments and not significantly related to rainfall amount or rainfall intensity (Table 1).

#### 4.1.2. Direct Effects of Traffic

Increases in sediment concentrations after the passage of a loaded truck ranged between 0–5, 0–8, and 0–10 g/L for the low, medium, and high intensity experiments, respectively. Unloaded trucks did not produce a measurable increase in sediment concentrations at the gutter outlet, except at very high rainfall intensities ( $>40$  mm/h). Smaller vehicles did not produce a measurable increase in sediment concentrations in gutter outflow either as they were narrow enough to only affect the eastern portion of the road that drained to the ditch. These results suggest that the weight of the truck affects sediment production during truck passage and a lower weight can generate sediment during higher rainfall intensities. Ziegler *et al.* [2001b] showed that both pickup truck and motor cycle passages led to increases in sediment production from a road section in northern Thailand and truck passages led to larger increases in sediment concentrations



**Figure 7.** The relation between background (nontruck influenced) sediment mass and the (a) 3 day and (b) 10 day Antecedent Precipitation Index, as well as the relation between the mass of sediment generated by the first loaded truck passage during an experiment and the (c) 3 day and (d) 10 day Antecedent Precipitation Index.

than motorcycle passes. Their experiments were conducted during much higher rainfall intensities (100–120 mm/h) than in this study.

The fraction of the total sediment mass generated from the road surface during an experiment directly caused by the passage of loaded trucks varied between 4 and 64% (Table 3). The mass of sediment generated by the passage of a loaded truck increased with precipitation intensity (Figure 4c). This nonlinear relation suggests the mass of sediment generated by a loaded truck may reach a maximum at a certain precipitation intensity, or there is greater variability in the mass of sediment generated by a loaded truck passage at higher precipitation intensities. The relation between the number of loaded trucks passing during an experiment and the total volume of sediment generated by loaded trucks during the experiment was not statistically significant, probably due to the small number of loaded trucks passing during each experiment and the small variation in the number of loaded truck passages during the experiments (Table 3). A significant relation between the number of loaded trucks passing during an experiment and the total volume of sediment generated by loaded trucks was expected based on the results of *Bilby et al.* [1989], who found that the number of axles during an event was one of the main factors in explaining the sediment concentrations in ditch flow. *Bilby et al.*'s [1989] suggestion that accumulation of fine sediment during heavy traffic buffers the road surface from further abrasion and sediment production, resulting in smaller sediment pulses from truck passages later during a rainfall event, was not observed for our medium and high intensity experiments either. The relation between the time into the experiment when a loaded truck passed and the volume of sediment the loaded truck produced was significant only for the low intensity experiments. The smaller number of loaded trucks observed later during the experiments, however, may have influenced the results for the high and medium intensity experiments.

The relation between the speed of a loaded truck (estimates ranged between 5 and 34 km/h) and the amount of sediment generated by the passage of the truck was not significant. A significant relation between the speed of a loaded logging truck and the amount of sediment it generates may become evident over a broader range of speeds and with a more precise method to measure speed. There was no significant relation between the mass of sediment directly generated by loaded truck passages during each experiment and the antecedent precipitation conditions either, even when looking only at the passage of the first loaded truck (Figures 7c and 7d). This suggests loaded trucks generate sediment pulses regardless of the antecedent precipitation conditions for the relatively wet conditions studied here, and the first minutes of precipitation (sprinkling) wet up the road enough to override any differences in antecedent wetness conditions.

#### 4.1.3. Controls on the Total Mass of Sediment Generated From the Road Surface

The total mass of sediment generated from the road surface during an experiment was linearly related to precipitation intensity (Figure 4d). This follows logically from the relation between the background sediment mass and precipitation intensity and the relation between the mass of sediment generated by a loaded truck passage and precipitation intensity (Figures 4a–4c). Similar to the relations for background sediment mass and the mass due to loaded truck passages, total sediment mass was more strongly related to precipitation intensity than total precipitation ( $R^2 = 0.81$  and  $0.59$  and  $p = 6 \times 10^{-9}$  and  $2 \times 10^{-5}$  for the relations between total sediment mass and precipitation intensity and total precipitation, respectively). The relations between the number of loaded logging trucks or the total number of vehicles passing through the site in the previous 1, 2, 3, 6, and 24 h periods and the total mass of sediment generated during a large-scale experiment were not consistently statistically significant, except for the medium intensity experiments, similar to the results for background sediment mass. ANOVA and  $t$  test results showed that the mass of sediment generated during the experiments with the different nozzles were statistically different. The total mass of sediment generated in experiments with and without traffic was only statistically significant for the high intensity experiments (nozzle 22 experiments).

The stepwise regression results showed that the total mass of sediment generated during an experiment depended on the precipitation intensity and the number of loaded trucks passing during a rainfall event ( $M = 0.72P + 0.51T$ , where  $M$  is the total sediment mass generated during the event in kg,  $P$  is the precipitation intensity in mm/h, and  $T$  is the number of loaded trucks passing during the event;  $R^2 = 0.86$ ; RMSE = 4.8 kg). Adding experiment duration, total rainfall amount, antecedent traffic conditions, or antecedent precipitation to the multiple linear regression did not significantly improve the coefficient of determination. This suggests that for events similar to the rainfall experiments (in terms of the range of rainfall intensities, duration, and antecedent conditions) the total amount of sediment produced from this section of the Mainline depends on the rainfall intensity and the number of loaded logging truck passages. Stepwise regression results of previous studies have shown that the amount of sediment produced by different road sections depended on road slope, time since last grading, roadbed gravel content, and precipitation [Sugden and Woods, 2007] or precipitation, slope, and grading [Ramos-Scharrón and MacDonald, 2005]. It is thus not surprising that precipitation was included in the stepwise regression, although precipitation intensity rather than precipitation amount was included as the dominant variable for these large-scale rainfall simulations. Gravel content (texture) and slope were not included in the stepwise regression as the regression equation developed in this study describes the variability in sediment production from one road section at different times, rather than the variability in sediment production for different road sections. We observed no effect of grading on sediment concentrations, most likely because the road was well maintained, grading was relatively minor and surficial (i.e., not as deep as in Ramos-Scharrón and MacDonald [2005], and all experiments were done within a relatively short period.

While this study was not designed to identify the physical properties of the road surface (mechanical strength, friction angle) and how this relates to mass erosion and fluvial processes, it was able to clearly identify the external drivers (rainfall rate and loaded logging truck passage) leading to sediment transport from the road surface. The results of the experiments suggest that sediment production from road surfaces can be considered both a fluvial and a mass erosion process. Each loaded truck passage loosens the sediment making it available for transport during rainfall events, implying that sediment production from the road surface could be treated as a mass erosion process that is dependent on the mechanical strength of the road material. Truck passages between events also loosen material that is flushed off during rainfall



events. This is in line with the hysteretic relation between sediment concentrations and road runoff showing the increase in runoff is preceded by an increase in concentrations, indicating a supply-limited sediment transport scenario. However, sediment concentrations (especially the steady state sediment concentrations) depended also highly on rainfall intensity, which indicates a fluvial process and a kinetic energy impact problem. In addition, the mass of sediment generated by a loaded logging truck passage was dependent on the rainfall rate, suggesting an interaction between fluvial and mass erosion processes.

#### 4.1.4. Ditch Flow Measurements

Flow at the weir, when it occurred, was delayed compared to gutter outflow. The initial peak in sediment concentrations observed in gutter outflow at the beginning of each experiment was not evident in weir sediment concentrations. Elevated sediment concentrations following the passage of loaded trucks were observed in the gutter outflow but not in the ditch (Figures 3c and 3e). Sediment concentrations in ditch water were generally lower than the background (nontruck influenced) sediment concentrations observed in the gutter during the first 90 min of the experiments. At later times during the experiments, sediment concentrations measured at the weir became similar to the background sediment concentrations observed in the gutter (Figures 3c and 3e). The lower steady state sediment concentrations observed at the weir during some experiments suggests significant mixing, dilution and storage occurred in the ditch. Observations in July 2010, showed substantial sedimentation (approximately 0.11 m, mainly clay and some silt) had occurred behind the weir plate since November 2009. We frequently observed flow from the settling ponds in the ditches along the road. They were thus not effective in retaining the sediment from the road during large events or wet periods.

#### 4.2. Small-Scale Rainfall Simulation Results

During the small-scale rainfall simulation experiments, sediment concentrations in hose outflow initially increased and then decreased to a steady state concentration, similar to the large-scale rainfall simulation results (Figure 3f). However, there was a large variation in the peak sediment concentrations and total mass of sediment generated during the small-scale rainfall simulation experiments (Table 2). This reveals a large spatial variability in sediment generation from the road surface, even within the same watershed. Steady state sediment concentrations at the end of each small-scale experiment, however, were relatively similar to the large-scale rainfall simulations using the same nozzle (Figure 3 and Tables 2 and 3). This suggests that the initial sediment supply varies along the road, which could be caused by differences in the quality of the bed material and the breakdown of the bed material, as well as differences in antecedent traffic conditions, drainage, or antecedent wetness conditions, even though antecedent wetness was not significantly related to sediment mass for the large-scale rainfall simulation experiments. The same ballast was used for the resurfacing of the road in 2007; therefore, it was assumed that the road material was relatively similar at all the sites. Unfortunately, no actual information on the spatial variability in texture or strength of the road surface material is available. The small-scale experiments were short in duration and did not have the same range of rainfall intensities, durations or exposure to vehicle traffic as the large-scale experiments, thus it is precarious to attribute the high degree of variability only to local conditions. It is possible that once a certain threshold of precipitation and or traffic is reached, local conditions play a smaller role in sediment production.

### 5. Summary and Conclusions

Twenty three large-scale and seven small-scale rainfall simulation experiments were conducted on an unpaved resource road in Haida Gwaii, BC to determine the controls on sediment generation, in particular, the influence of rainfall intensity, rainfall amount, antecedent precipitation, and traffic intensity. The large spatial variability in initial sediment concentrations demonstrated by the small-scale experiments indicate that extrapolation from one road section to another must be done cautiously.

The large-scale rainfall simulation experiments showed that precipitation intensity controlled the amount of sediment generated from the surface of the Mainline. The number of passages of loaded trucks during an experiment was the second most dominant control. The lack of a significant relation between the duration of an event and the total mass of background sediment generated from the road surface suggests that for rainfall events shorter than 5 h, in the absence of traffic, it is the initial sediment peak that controls the total mass of sediment generated from the Mainline, not the steady state sediment removal rate reached later in

the event. Peak sediment concentrations were related to antecedent traffic conditions, in particular the number of trucks passing through the site before the start of the experiments. The hysteretic relations between sediment concentrations and road runoff, where the increase in runoff was preceded by the increase in concentrations, suggest a supply-limited erosion scenario.

Each loaded truck passage resulted in a new sediment pulse, likely due to aggregate breakdown, the upward forcing of fine-grained material, or the breakdown of the armor layer. Because surface material could in some places be crushed by hand, it is probable that aggregate breakdown was an important factor. Elevated sediment concentrations in road surface runoff persisted for 30 min following the passage of a loaded truck during low rainfall intensity experiments and for shorter times at higher rainfall intensities. The mass of sediment generated during a truck passage increased with rainfall intensity. Unloaded truck passages only caused measurable increases in sediment concentrations during extreme rainfall conditions. The relatively low fraction of total sediment mass directly due to loaded truck passages (<30% for all but one experiment) indicates significant amounts of sediment would be generated even if no loaded trucks were present during rainfall events and thus suggest that closure of roads during rainfall events will not eliminate sediment production from the Mainline. However, based on these rainfall simulations, closure to loaded trucks during rainfall events could reduce erosion by 4–64% for the Mainline.

The large variability in initial responses and peak sediment concentrations demonstrated by the small-scale experiments, indicate that local conditions (such as antecedent traffic, drainage and aggregate quality) may control peak road surface erosion rates along the Mainline. This suggests that replication of the large-scale experiments would be required if the objective is to determine the peak sediment concentrations or peak erosion rates for the entire road network or large sections of roads with highly variable local conditions. Identifying precipitation and traffic thresholds and better describing the spatial and temporal variability at multiple locations will be important to improve estimates of sediment production from unpaved resource roads and to identify management strategies to reduce sediment delivery to streams.

#### Acknowledgments

We would like to thank the BC Ministry of Forests, Lands, and Natural Resource Operations for providing equipment and extensive in kind support and Larry Duke for his personal support and involvement with the project in particular. Funding for this work was provided by Island Timberlands, BC Timber Sales and the Village of Queen, as well as a MITACS BC internship grant and an NSERC Discovery grant. Senninger Irrigation Inc. and the Burnaby Fire Department generously donated some of the equipment used in the construction of the rainfall simulator. Figure 1 was created by John Ng (Simon Fraser University).

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